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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF THE COMBUSTION OF A 50 PERCENT PENTABORANE - 50 PERCENT JP-4 FUEL BLEND IN A TURBOJET COMBUSTOR AT SIMULATED ALTITUDE CONDITIONS

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NATIONAL ADVISORY COMMITTEE
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RESEARCH MEMORNADUM

PRELIMINARY INVESTIGATION OF THE COMBUSTION OF A 50 PERCENT PENTABORANE - 50 PERCENT JP-4 FUEL BLEND IN A TURBOJET COMBUSTOR AT SIMULATED ALTITUDE CONDITIONS

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SUMMARY

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A preliminary investigation was conducted to determine the combustion characteristics of a fuel composed of 50 percent pentaborane and 50 percent JP-4 (MIL-F-5624A) by weight in a turbojet combustor. A combustor designed to fit the housing of a J33-A-23 turbojet engine was selected for convenience. The fuel was evaluated at two engine conditions simulating altitudes of 40,000 and 57,000 feet, an engine speed of 85 percent of rated rpm, and a flight Mach number of 0.6. The pentaborane blend was initially evaluated in combustors developed for pure pentaborane and diborane reported in NACA RM E53B18 and RM E52L15. The performance of the blend was unsatisfactory in these combustors. A new combustor was then developed which provided combustor efficiencies measured from 91 to 101 percent as compared with efficiencies of 92 to 94 percent previously obtained for pentaborane at comparable conditions. Additional refinements of design details are needed to obtain lower oxide deposits and a more uniform outlet temperature profile; however, the combustor is believed to incorporate some of the design principles required to obtain satisfactory over-all performance with the fuel blend investigated.

INTRODUCTION

Special fuels are being investigated at the NACA Lewis laboratory in an effort to extend the range, thrust, and operational limits of jet-propelled aircraft. Fuels of interest for use in turbojet-powered aircraft include pentaborane, diborane, and mixtures of these boron hydrides with hydrocarbon fuels. These fuels are of interest because they possess desirable heating values and chemical reactivity. However, the use of these fuels introduces special problems, inasmuch as the combustion products contain boron oxides which exist in solid and liquid states at current turbojet-engine exhaust temperatures. An additional problem that exists with pentaborane is that under the proper conditions this fuel is spontaneously inflammable at normal room temperatures (ref. 1).

It is possible to blend pentaborane with hydrocarbon fuels currently used in turbojet engines. Although the heating value of the blend is reduced with the addition of a hydrocarbon, the availability and the handling characteristics are improved. Reference 1 has shown that liquid pentaborane will react with air at room temperature if sufficient liquid is present and will burst into flame after a short induction period. If the liquid is initially warmed to a temperature of 113° F, it will burst into flame immediately. Diluting the pentaborane with a hydrocarbon, such as 3-methylpentane, raises the spontaneous-ignition 3132
temperature from 113° to 252° F for a 70-percent blend of pentaborane and to 418° F for a 50-percent blend of pentaborane. Therefore, on the basis of the increased availability and improved handling characteristics, it was of interest to evaluate a representative hydrocarbon-pentaborane blend in a turbojet combustor.

Experimental investigations of the combustion characteristics of diborane and pentaborane in turbojet combustors, initiated at the request of the Bureau of Aeronautics, Department of the Navy, as part of Project Zip, have been conducted at this laboratory and are reported in references 2 and 3. The preliminary results of the evaluation of diborane and pentaborane indicated that it was necessary to design specific combustors for each fuel to obtain high combustion efficiency and minimize solid oxide deposits on the walls of the combustor. Experimental combustors were developed which gave satisfactory performance at the limited test conditions and short durations investigated. Promising techniques were demonstrated for alleviating oxide deposits on turbine blades and other metal surfaces, namely, by heating or by filming the surfaces with air.

The results reported herein on a 50-percent blend of pentaborane in JP-4 (MIL-F-5624A) fuel were obtained during February and March of 1953 as a continuation of research reported in references 2 and 3. During the investigation of the pentaborane blend, two fuel injectors and two combustor modifications were tested. Test conditions simulated altitudes of 40,000 and 57,000 feet, an engine speed of 85-percent rated engine rpm, and a flight Mach number of 0.6. Data are presented on combustion efficiencies, outlet temperature profiles, and oxide deposits.

FUEL

Source. - The fuel used in this investigation was obtained through the cooperation of the bureau of Aeronautics, Department of the Navy. The purity of the pentaborane component was 99 percent.

Properties. - Values of several of the physical properties of the fuel and the pentaborane component are as follows:

	Pentaborane[a]	50 Percent pentaborane and 50 percent JP-4 by weight
Formula weight	63.17	----------
Melting point, °F	-52	-90
Boiling point, °F at 760 mm Hg	136	----------
Heat of combustion, Btu/lb	[b,c]29,127	23,800
Heat of combustion, Btu/cu ft	[d]1,108,000	[e]1,035,000
Stoichiometric fuel-air ratio	0.07635	0.0715

[a]Pure.
[b]Based on H_2O in gaseous phase.
[c]Value used in this report. Most recent value is 29,100.
[d]Specific gravity of pentaborane taken as 0.61 at 0° C.
[e]Specific gravity of the blend at 0° C.

Values for the density and volatility of the blend are shown in table I. The physical properties of the blend are unpublished data obtained from Mathieson Chemical Corporation. The melting points of the two forms of boron oxide, B_2O_3, are as follows:

Crystalline, °F 842
Vitreous, °F 1070

FUEL SYSTEM AND OPERATING PROCEDURE

The fuel system is shown in figure 1 and is similar to that used in references 2 and 3. Methyl cellosolve used as the coolant was kept at a temperature of 80° to 100° F. The coolant was circulated through chamber B and the jacketed fuel line and nozzle housing, if used.

The fuel tank was suspended in the coolant chamber by a cantilever arm connected to a strain gage. In some tests no coolant was used in the coolant chamber; hence, the buoyant forces of the coolant were absent. Each fuel tank was fitted with a siphon extending to the bottom of the cylinder and a gas inlet located at the top of the cylinder. Fuel was forced from the tank by helium pressure, which was controlled by a remotely operated regulator. The helium pressure was preset and the fuel flow was started and stopped by a remotely controlled pressure-operated piston valve. The fuel-flow rate was governed by the applied helium pressure and by the size of the injection nozzle. The sleeve, extending from the coolant level to the bottom of chamber B, protected the fuel tank and strain gage from the flow forces of the circulated coolant if used. Coolant-bath density changes were insignificant during any run. Fuel lines were purged with helium before and after each run.

Figure 2 shows the details of the injection systems tested. Two types of injector were used - a simple discharge orifice (I) developed for use with pentaborane (ref. 3) and a swirl-type nozzle (II) developed for use with diborane (ref. 2).

APPARATUS

<u>Combustor installation</u>. - A diagram of the combustor installation is presented in figure 3. Combustion air from the central laboratory supply 3132
was regulated by a remote-control valve. The combustor-inlet temperature was regulated by a heat exchanger. The exhaust products of the test chamber were discharged into an exhaust plenum where they were cooled by water sprays and discharged through an exhaust header. The header was valved to provide either atmospheric or altitude exhaust. The lowest exhaust plenum operating pressure obtainable with the altitude exhaust system was 0.45 atmosphere absolute.

<u>Combustors</u>. - Two combustors were tested, the combustor which exhibited the best performance with pentaborane (model 7 of ref. 3), and the combustor which gave best performance with diborane (model 6 of ref. 2). The model 7 combustor is shown in figure 4(a), and the model 6 combustor is shown in figure 4(b). These combustors were designed to fit a 7-inch-diameter combustor housing from a J33-A-23 turbojet engine. The dome of the model 7 combustor was fabricated of porous screen which was silver-soldered to the liner. The screen material was untreated, 28×500-mesh stainless-steel wire cloth. The air flow passing through the screen was estimated to be one-fourth of the total air flow. The model 7 combustor was used with fuel injectors I and II (figs. 2(a) and (b)). When this combustor was used with fuel injector I, the standard fuel-injector support strut was cut off at the wall of the adapter piece leading to the combustor housing. The fuel tube of injector I was supported at the adapter wall. A spark plug was used as an ignition source; the location and type of electrode of the spark plug used during the various test runs are shown in figure 5.

<u>Apparatus for oxide-deposit studies</u>. - The apparatus for studying the oxide-deposit problem was similar to that used in references 2 and 3 and consisted of a bank of 1/2-inch-diameter tubes extending across the combustor exhaust duct. Each of the tubes was designed to evaluate different techniques for reducing turbine blade deposits. One tube was sealed on both ends so that its surface temperature would approach the temperature of the gas stream. The second tube was water-cooled. The third tube had provision for being heated above the gas-stream temperature by passing current from an electric-arc welder through the tube; however, this tube was not electrically heated during the series of tests reported herein. The fourth tube was formed from porous cloth through which 80° F air was passed to provide a cool-air film surrounding the tube.

Instrumentation. - Air flow was metered by an A.S.M.E. orifice. The pressure upstream of the orifice, fuel-tank pressure, and the exit plenum pressure were indicated by calibrated gages. The orifice pressure differential was indicated by a water-filled manometer. The combustor-inlet and exit total pressures were indicated by mercury-filled manometers.

The fuel weight was recorded continuously by means of a strain gage and an oscillograph. The fuel-weighing system was calibrated immediately
3132 before each run. The fuel-flow rate was computed from the slope of the fuel weight-time curve. An independent check of the flow rate was provided by weighing the fuel tank by means of a balance scale before and after each run. The loss of fuel during the purging process was deducted from the scale difference weights. This loss was computed from the fuel-line volume. The two methods of fuel-flow-rate measurement for the pentaborane blend tests conducted in the present investigation agreed within 6 percent.

Figure 6 shows the general construction and location of the 16 thermocouples at the combustor outlet; the bare-wire couples used in run 25 were replaced with closed-end couples for runs 26, 27, and 28. Single thermocouples were used to indicate the combustor-inlet air temperature, fuel temperature near the injection nozzle, fuel inlet temperature, and the temperature of the tubes used to simulate the turbine blades. The more important temperatures were recorded at regular intervals during each test by self-balancing strip-chart potentiometers. Additional temperatures were manually recorded from the readings of self-balancing potentiometers.

PROCEDURE

Test conditions. - Two test conditions were investigated as follows:

Test condition	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet temperature, °F	Air flow[a], lb/(sec)(sq ft)	Combustor temperature rise, °F	Simulated flight conditions[b]	
					Altitude, ft	Percent of rated rpm
A	34	268	6.32	680	40,000	85
C	15	268	2.83	680	57,000	85

[a]Air flow per unit of maximum cross-sectional area of combustor housing.

[b]Simulating a flight Mach number of 0.6 in a typical turbojet having a 5.2:1 compressor pressure ratio at sea level and rated rpm.

Calculation. - On each run, one or more points were chosen for analysis from the temperature strip charts. These points represent the midpoint of an interval of exit temperature equilibrium.

Combustion efficiencies were computed from the following approximate relation:

$$\eta_b = \frac{\text{Equivalence ratio theoretically required for measured temperature rise}}{\text{Actual equivalent ratio}}$$

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The theoretically required equivalence ratios for a measured temperature rise were determined from unpublished results by the method and assumptions described in references 4 and 5.

Accuracy. - The accuracy of the combustion-efficiency data was estimated to be within ±5 percent and was determined primarily by the accuracy of the fuel-flow measurement.

Development procedure. - The actual combustion behavior of the pentaborane JP-4 blend was unknown. Hence, as a starting point the fuel was first evaluated in the combustor and fuel-injection system (figs. 4(a) and 2(a)) which gave the best performance in the pentaborane investigation reported in reference 3. The blend fuel was next evaluated in the combustor and fuel-injection system (figs. 4(b) and 2(b)) developed in the preliminary diborane investigation (ref. 2). From the results obtained in these combustors, a new combustor was fabricated to incorporate the better features of each. Final evaluation of the fuel blend was made in this composite combustor.

RESULTS AND DISCUSSION

The experimental results obtained in the various combustor modifications are presented in chronological order in table II. The experimental test conditions are also listed in table II; these values did not meet the target test conditions in all cases. Some of the significant results of the various tests are discussed in the following paragraphs.

Evaluation in the Pentaborane Combustor

The combustor developed in reference 3 for pentaborane (fig. 4(a)) was based on the following assumptions:

1. Recirculation and the turbulence of the combustion air upstream and for several inches downstream of the fuel injector should be minimized.

2. The jet of liquid fuel should not impinge on the walls of the combustor.

3. The spark-ignition electrodes should not be placed near the fuel-injection zone since the electrodes introduce surfaces where the deposits could form and thereafter bridge to the injection nozzle.

To avoid the tendency of oxides to form on the spark electrode the
3132 ignition source was introduced downstream of the instrumentation section. A conventional spark plug was used at this position. Ignition was unsuccessful at an equivalence ratio corresponding to test condition A. At somewhat richer equivalence ratios, ignition was obtained; however, when the fuel flow was decreased flame-out occurred prior to the desired operating conditions. This phenomenon accounts for the off-condition data reported in the table for run 25. The combustion efficiency for test run 25 was approximately 80 percent. The outlet temperature profile is shown in figure 7. A temperature variation of at least 660° F existed. The nozzle deposit was negligible and the deposit of the combustor liner plus dome was only 40 grams. A photograph of the combustor liner after the test run is shown in figure 8. The low combustion efficiency, poor stability, and large temperature variations indicated that the combustor developed in reference 4 for pentaborane was not suitable for a 50-percent blend of pentaborane and JP-4.

Evaluation in the Diborane Combustor

The next configuration tested is shown in figure 4(b) and the data are listed as run 26 in table II. Ignition was satisfactory at an equivalence ratio corresponding to condition A. Combustion efficiency was approximately 100 percent. The combustor-outlet temperature profile was considered acceptable and is shown in figure 9. However, the deposits were considered excessive in the vicinity of the dome as can be seen in figure 10; hence a further combustor modification appeared desirable.

Evaluation in the Composite Combustor

The third and final configuration consisted of the model 7 combustor (fig. 4(a)) developed for pentaborane and the fuel injector (fig. 2(b)) developed for diborane. The aforementioned configuration was selected in order to combine the spray-type injector which gave good combustion characteristics with the porous screen dome which gave little oxide deposits. Stable combustion was achieved at the two test conditions investigated; however, the spark plug had to be extended to the center of the combustor in order to obtain ignition at test condition C. The combustion efficiency of the blend was 101 and 91 percent at test conditions A and C, respectively. Efficiencies previously obtained with pentaborane in reference 4 were 94 and 92 percent for the respective test conditions. The combustor-outlet temperature profiles for runs 27 and 28 corresponding to test conditions A and C are presented in figures 11(a) and (b). Photographs of the combustor and nozzle after the tests are shown in figures 12 and 13. The tendency for deposits to adhere to the liner appeared to be less for the blend than for the previous tests of pentaborane.

The composite combustor (model 7 liner with fuel injector II) produced high combustion efficiencies at the conditions investigated. Additional tailoring of design details is needed to obtain lower oxide deposits and a more uniform outlet temperature profile; however, the combustor is believed to incorporate some of the design principles that are required to obtain satisfactory over-all performance with the fuel blend investigated. 3132

Techniques for Eliminating Deposits

The tubes installed at station D-D of figure 3 to evaluate the various techniques for alleviating turbine deposits are shown in figures 14 and 15 for the various test runs. The rod third from the left, which had provisions for being heated, was not functioning during these tests; hence, it was essentially at the same condition as the dummy rod, the first on the left. Figures 14(a), (b), and (c) were at test condition A; hence, the inlet conditions to the rods were similar with the exception of the local outlet temperature profile variations, as can be seen by referring to figures 7, 9, and 11. In all cases a heavy deposit was formed on the dummy rod, rod 1. Rod 2, the water-cooled rod, showed that the products of combustion from the pentaborane JP-4 blend had a definite tendency to spall off the cooled surfaces. A similar tendency was reflected on the air-film-cooled rod on the extreme right. The pressure drop across the tube wall of this porous wire-cloth tube was approximately 3 inches of mercury. The tube wall temperature was well below the oxide melting point. Figure 15 shows the deposits formed at test condition C. Again the same pattern results are observed. The dummy rod, which was essentially at gas-stream temperature, allowed a heavy deposit to form. The water-cooled rod and the air-cooled rod produced spalling of the oxide deposit. Thus, these data indicate that there is some promise for alleviating oxide deposits on turbine blades or other metal parts exposed to the combustion products of boron-containing fuels by using methods designed to induce spalling of the metal oxides. Furthermore, examination of the rods operating at temperature equilibrium with the gas stream showed that, in regions where the gas temperature was well above the melting point of the oxide, only a thin film of the oxide adhered to the surface of the tube.

SUMMARY OF RESULTS

The results obtained in the investigation of the blend of 50 percent pentaborane in JP-4 (by weight) in a 7-inch-diameter turbojet combustor are summarized as follows:

1. Low combustion efficiencies and poor temperature profiles resulted when the pentaborane blend was burned in a combustor that had previously been developed to give satisfactory performance with pentaborane. The pentaborane blend evaluated in the combustor that had previously been developed to give satisfactory performance with diborane gave a high combustion efficiency, but severe oxide deposits formed near the upstream portion of the combustor liner.

2. An experimental combustor was developed for the pentaborane blend which exhibited smooth and stable combustion; however, the exit temperature variation was greater than desired. Combustion efficiencies ranged from 91 to 101 percent as compared with efficiencies of 92 to 94 percent previously reported for pentaborane in NACA RM E53B18. Oxide deposits were similar to the deposits in the better configuration of RM E53B18 developed for pentaborane.

3. Techniques were demonstrated for alleviating oxide deposits on surfaces at the turbine stator blade station; namely, filming surfaces with air, shock chilling, and maintaining the surfaces above the melting point of the oxide.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 22, 1953

REFERENCES

1. Fletcher, Edward A.: Spontaneous Flammability of Pentaborane and Pentaborane - 3-Methylpentane Blends. NACA RM E53I17, 1957.

2. Kaufman, W. B., Gibbs, J. B., and Branstetter, J. R.: Preliminary Investigation of Combustion of Diborane in a Turbojet Combustor. NACA RM E52L15, 1957.

3. Gibbs, J. B., Kaufman, W. B., and Branstetter, J. R.: Preliminary Investigation of the Combustion of Pentaborane and Diborane in a Turbojet Combustor at Simulated Altitude Conditions. NACA RM E53B18, 1957.

4. Breitwieser, Roland, Gordon, Sanford, and Gammon, Benson: Summary Report on Analytical Evaluation of Air and Fuel Specific-Impulse Characteristics of Several Nonhydrocarbon Jet-Engine Fuels. NACA RM E52L08, 1953.

5. Tower, Leonard K., and Gammon, Benson E.: Analytical Evaluation of Effect of Equivalence Ratio, Inlet-Air Temperature, and Combustion Pressure on Performance of Several Possible Ram-Jet Fuels. NACA RM E53G14, 1953.

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TABLE I. - ANALYSIS OF FUEL BLEND COMPOSED OF 50 PERCENT PENTABORANE AND 50 PERCENT JP-4 (MIL-F-5624A) BY WEIGHT

Fuel properties	
A.S.T.M. distillation, $^{\circ}F$	
Initial boiling point	139
Percent evaporated	
10	145
20	151
30	156
40	164
50	176
60	---
70	313
80	336
90	356
95	375
97.5	382
Reid vapor pressure, lb/sq in.	4.6
Specific gravity, $^{\circ}C/4^{\circ}$ C	
0	0.697
10	.689
15	.685
20	.681
25	.677
30	.673
35	.669

[redacted]

[redacted]

TABLE II. - OPERATING CONDITIONS AND RESULTS

Run	Combustor model	Fuel nozzle	Test condition	Duration of operation, min	Combustor-inlet temperature, T_1, °F	Combustor-inlet total pressure, P_1, in. Hg abs	Air flow, lb/(sec)(sq ft)	Fuel flow, lb/sec	Equivalence ratio	Combustor temperature rise, °F	Combustor efficiency, percent	Fuel-injector pressure differential, lb/sq in.	Combustor velocity, ft/sec	Average combustor-outlet temperature, °F	Maximum individual outlet temperature, °F	Minimum individual outlet temperature, °F	Time data recorded, min	Deposit (liner plus dome), g	Nozzle deposit, g	Combustor pressure losses, $\frac{P_A-P_C}{q_r}$
25	7	I	A	2.3	276	37.5	6.33	0.0169	0.140	766	[a]84	200	94	1042	1460	800	0.5	40	0	23
26	6	II	A	6.0	274	40.1	6.30	.0110	.091	608	100	150	87	882	1270	670	5.0	[b]107	2	20
27	7	[c]II	A	6.2	268	37.6	6.30	.0116	.097	680	101	110	92	948	1480	480	3.4	66	1	19
28	7	[c]II	C	10.6	271	16.3	2.88	.0060	.109	657	91	140	87	926	1260	480	3.0	76	1	26

[a]Estimated efficiency on basis of 13 out of 16 outlet thermocouples.

[b]Including 15-gram deposit on spark plug.

[c]Nozzle tip located 0.9 inch downstream of plane of porous screen.

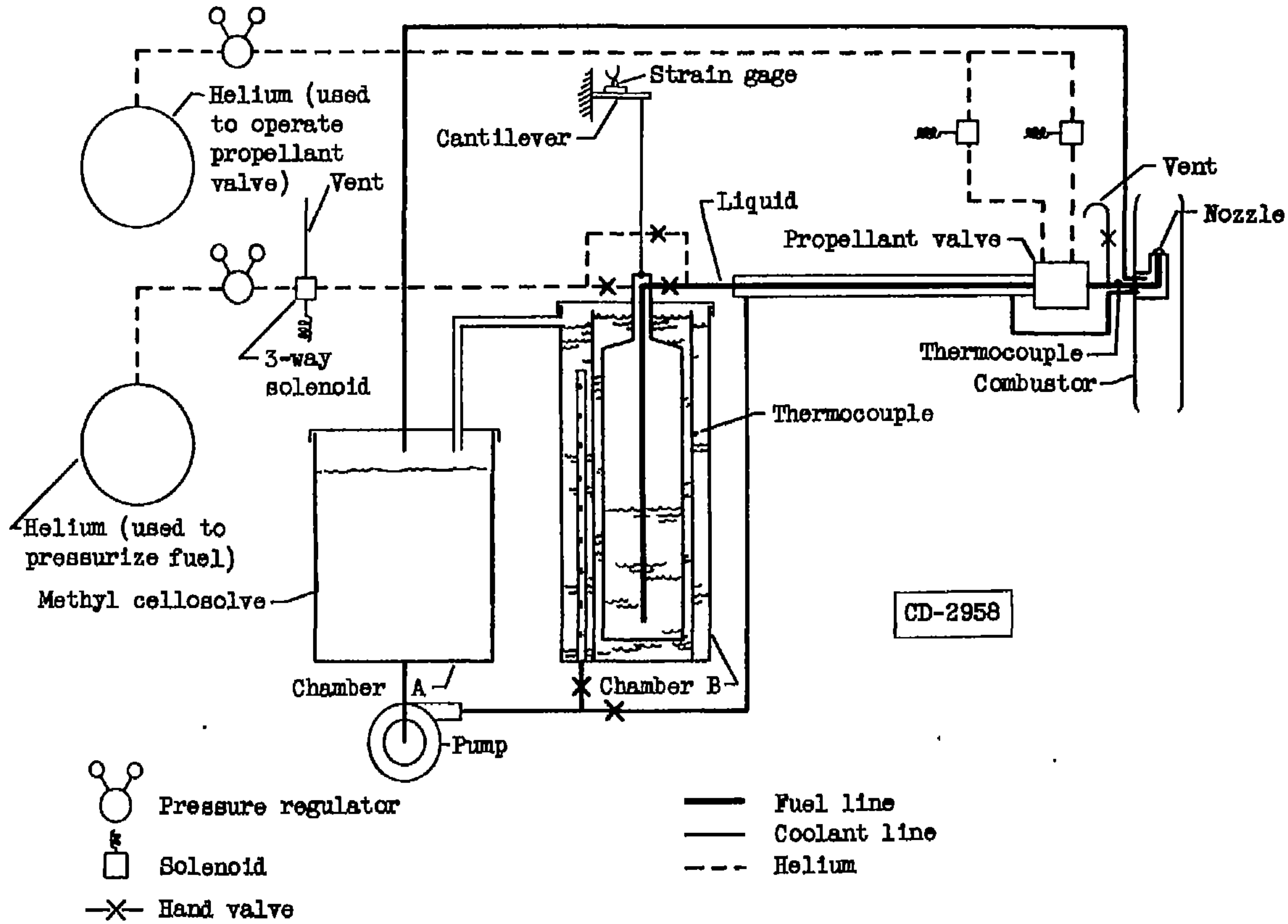
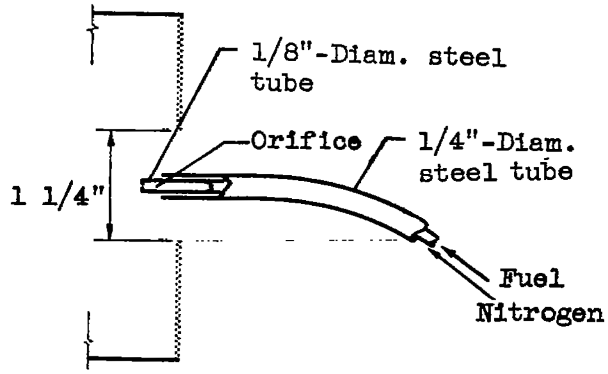


Figure 1. - Fuel system.



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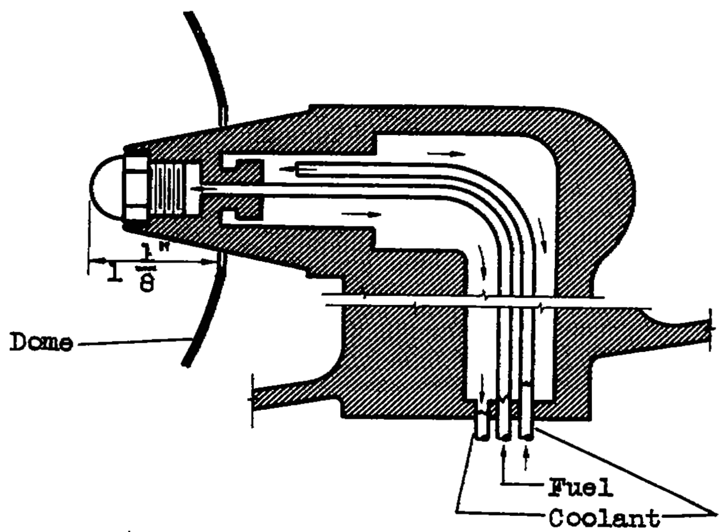
(a) Nozzle I developed for pentaborane (ref. 3).



(b) Nozzle II developed for diborane (ref. 2).

Figure 2. - Fuel-injection nozzles.

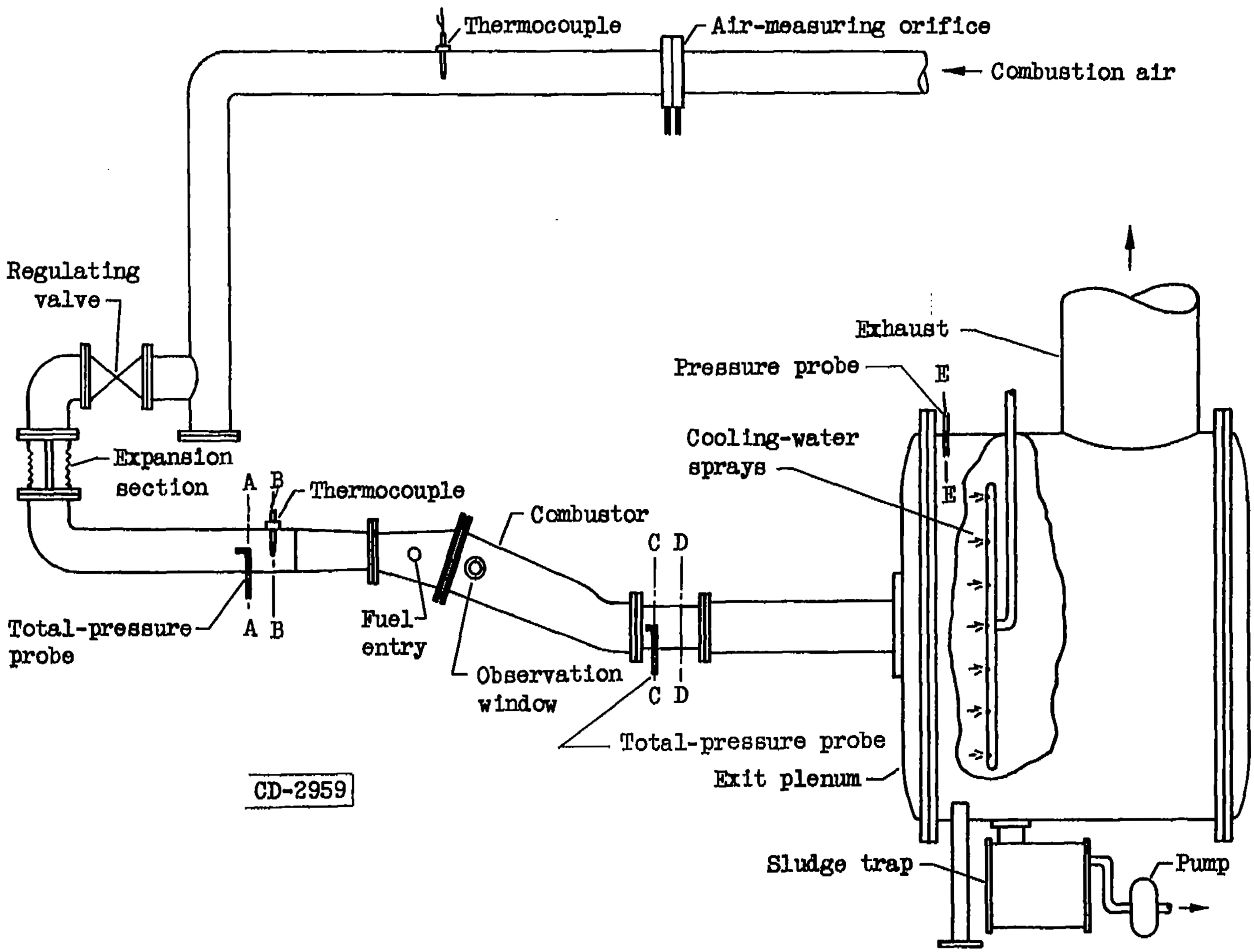


Figure 3. - Combustor installation.

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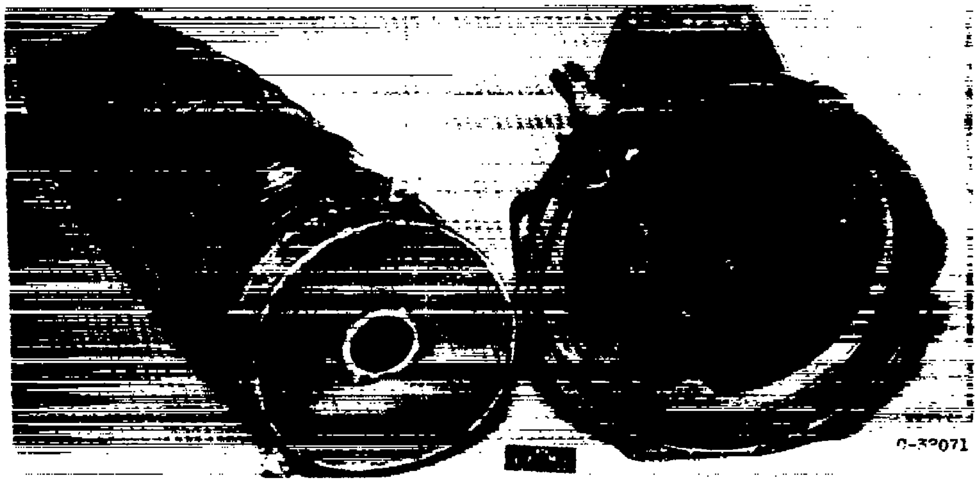
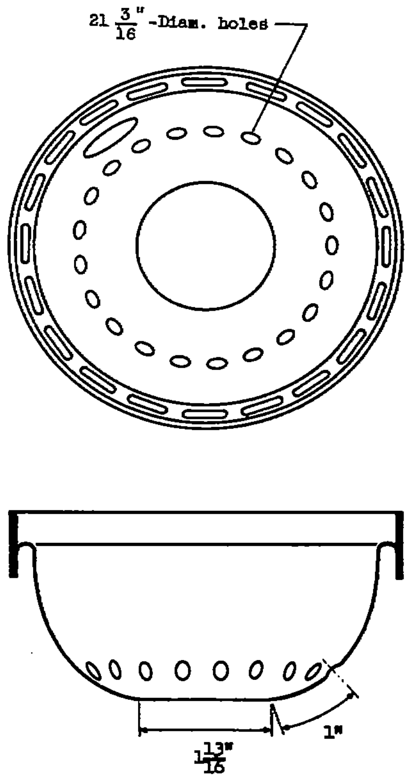
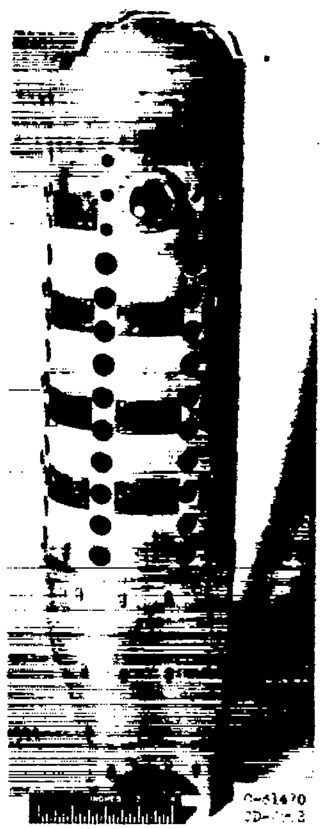


(a) Model 7 developed for pentaborane (ref. 3).



Dome



Dome and liner assembly

(b) Model 6 developed for diborane (ref. 2).

Figure 4. - Combustors.

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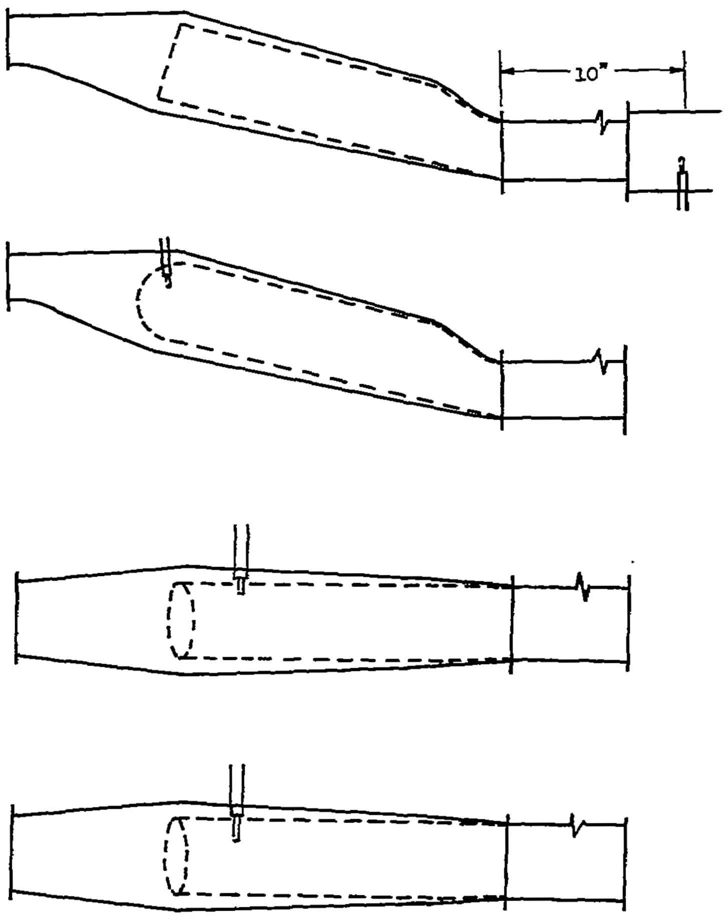

Run 25; standard plug with elongated electrodes. Side view.

Run 26; standard plug with elongated electrodes. Side view.

Run 27; standard plug in cross-over port. Top view.

Run 28 (after initial trial); standard plug with elongated electrodes. Top view.

Figure 5. - Location and type of ignition source.

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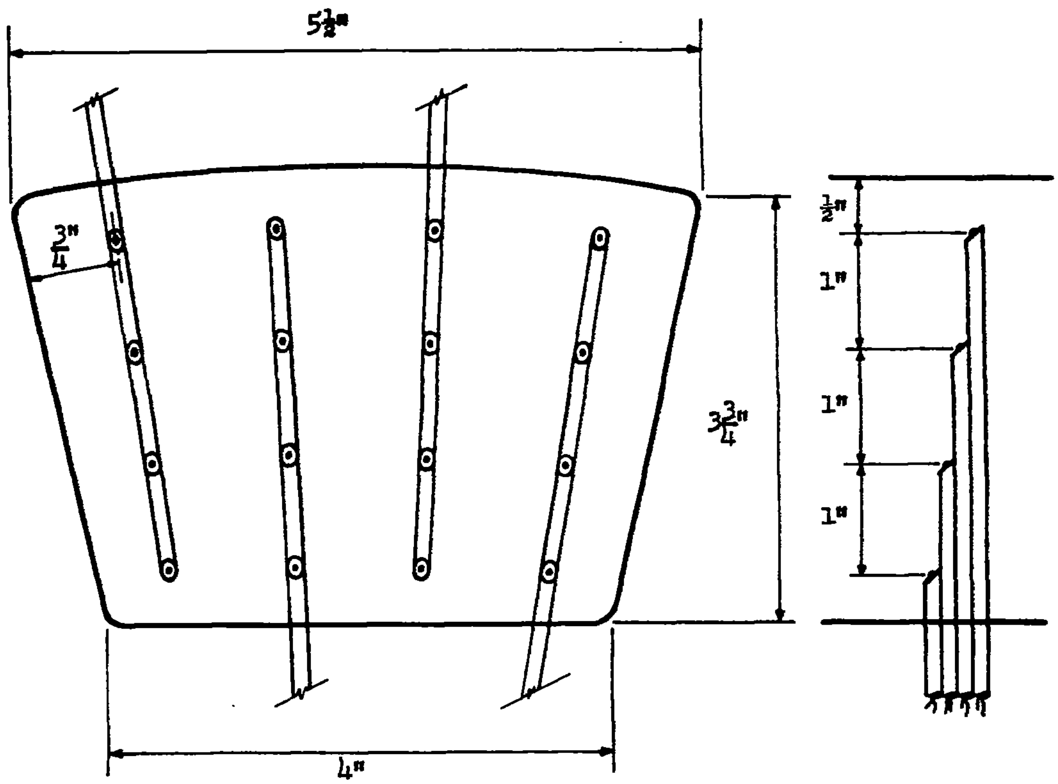

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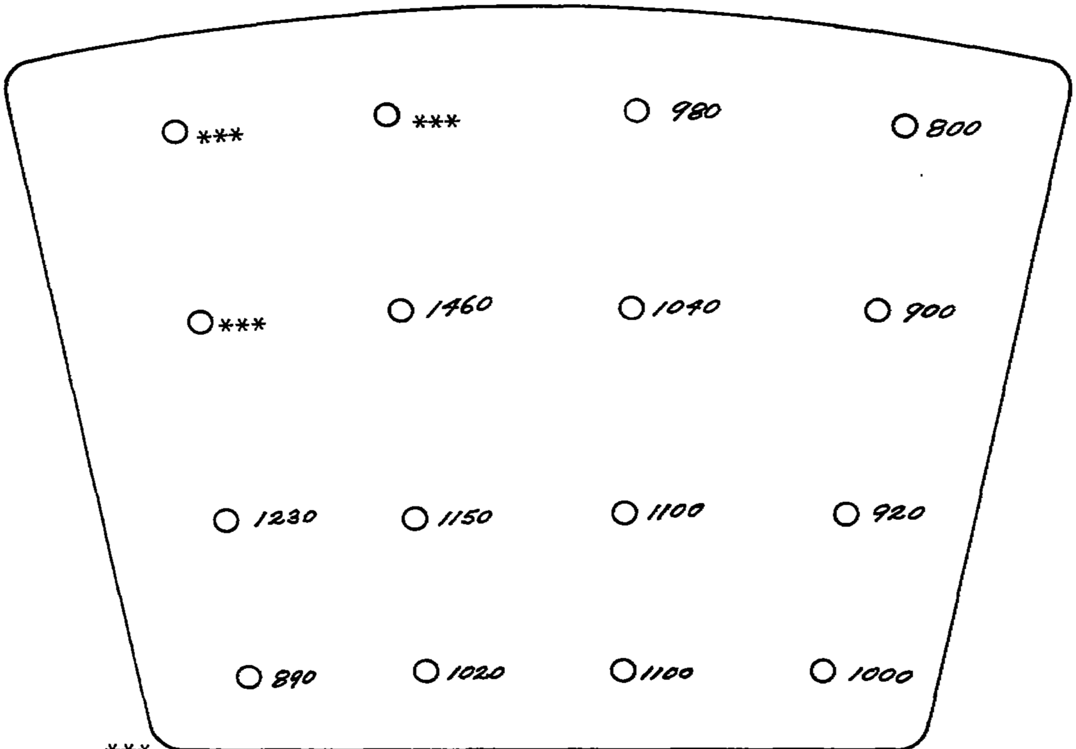
Figure 6. - Combustor-outlet instrumentation.



***Thermocouple failed (open connection) during test.

Run 25; model 7 combustor; fuel nozzle I; test condition A.

Figure 7. - Outlet temperatures. Fuel, 50 percent pentaborane, 50 percent JP-4 blend. (Temperature in °F.)

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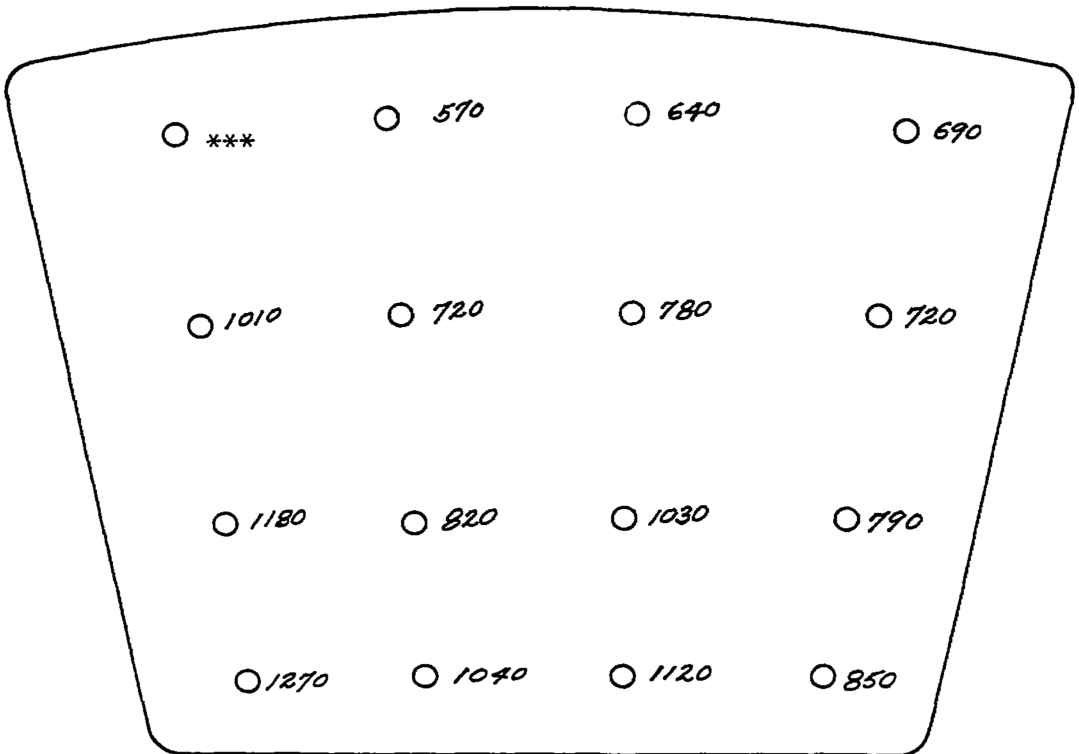
Figure 8. - Deposits with model 7 combustor and fuel-injection nozzle I. Fuel, 50 percent pentaborane, 50 percent JP-4 blend; run duration, 2.3 minutes at test condition A.



***Thermocouple failed (open connection) during test.

Run 26; model 6 combustor; fuel nozzle II; test condition A.

Figure 9. - Outlet temperatures. Fuel, 50 percent pentaborane, 50 percent JP-4 blend. (Temperature in °F.)

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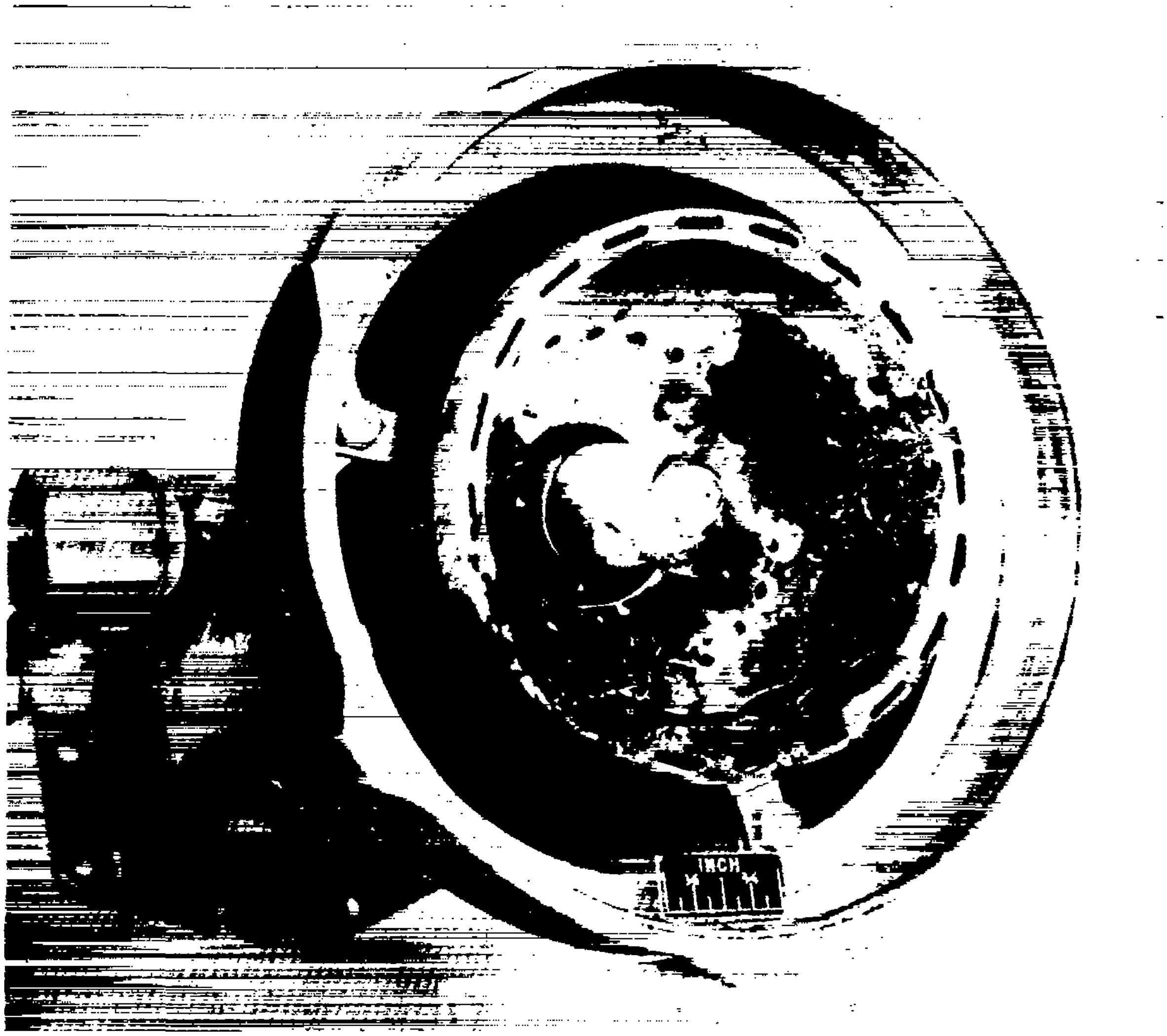

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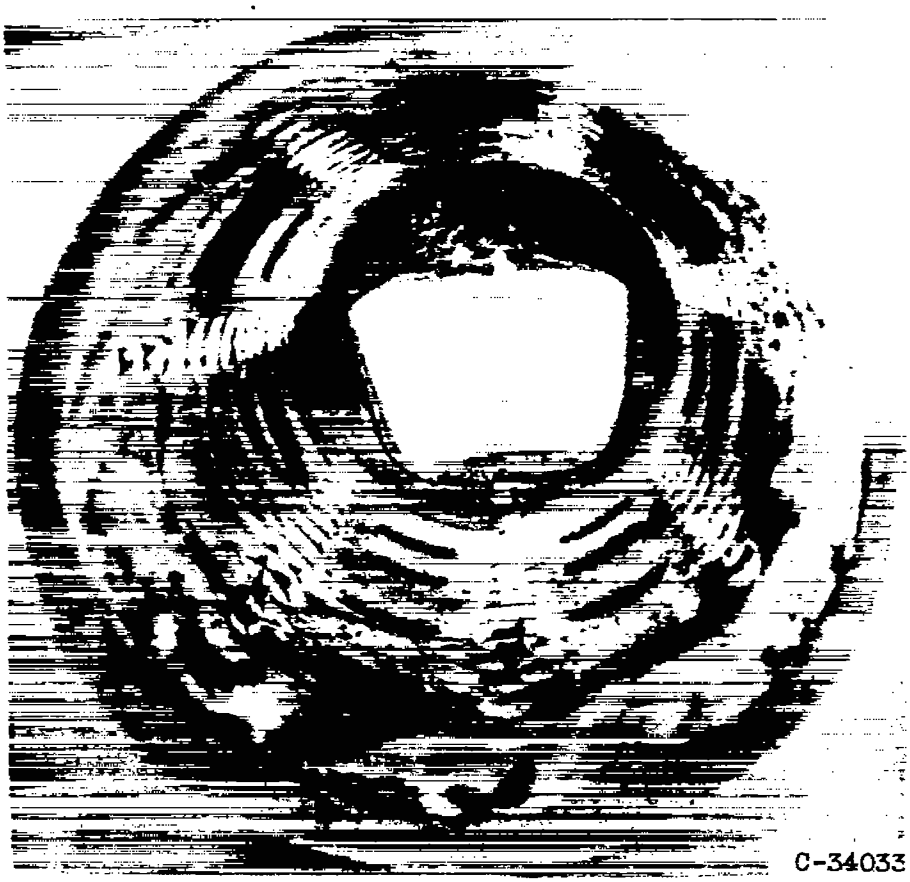
(a) Combustor dome.

Figure 10. - Deposits with model 6 combustor and fuel-injection nozzle II. Fuel, 50 percent pentaborane, 50 percent JP-4 blend; run duration, 6.0 minutes at test condition A.



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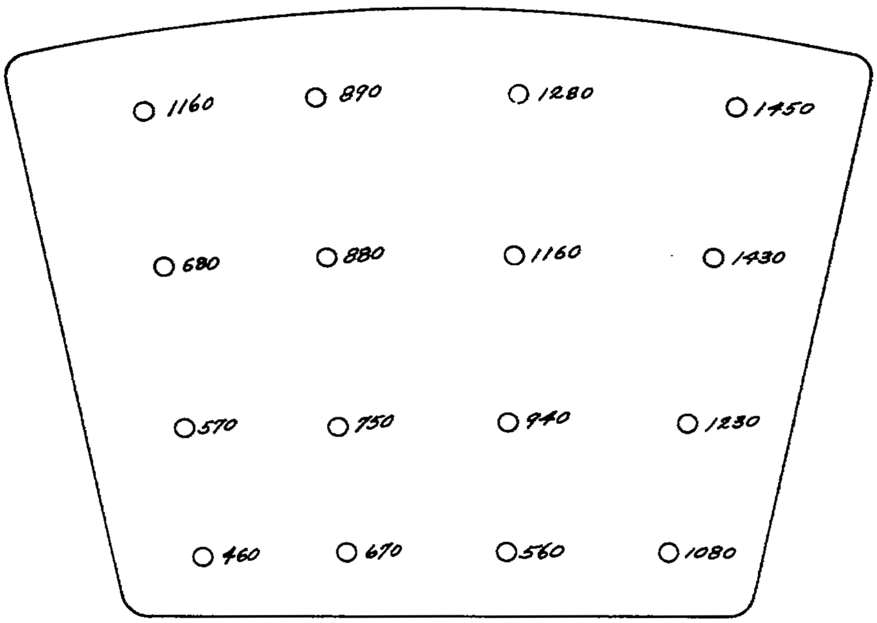
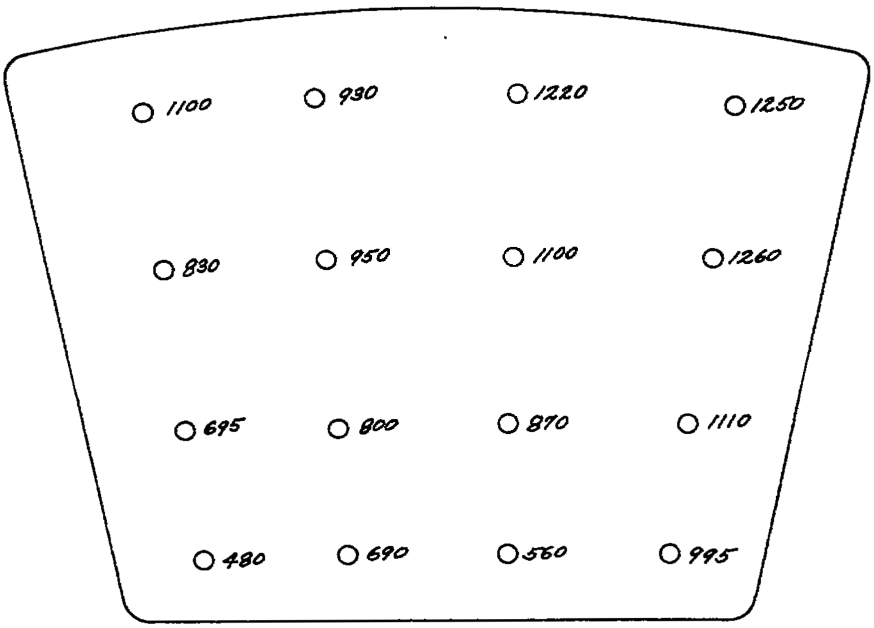
(b) Combustor liner.

Figure 10. - Concluded. Deposits with model 6 combustor and fuel-injection nozzle II. Fuel, 50 percent pentaborane, 50 percent JP-4 blend; run duration, 6.0 minutes at test condition A.

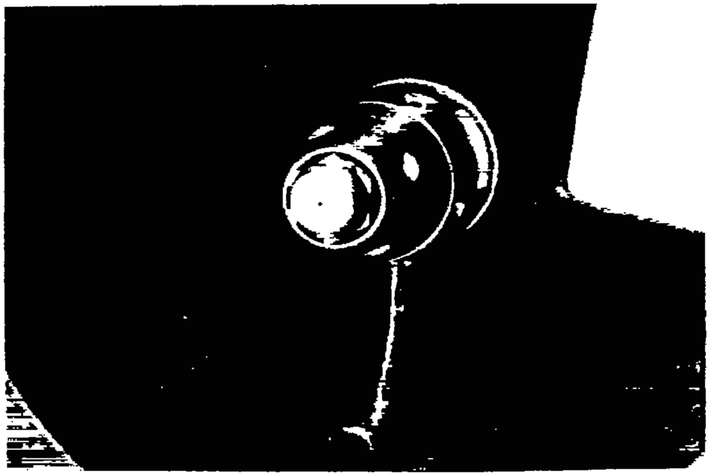


(a) Run 27; model 7 combustor; fuel nozzle II;
test condition A.

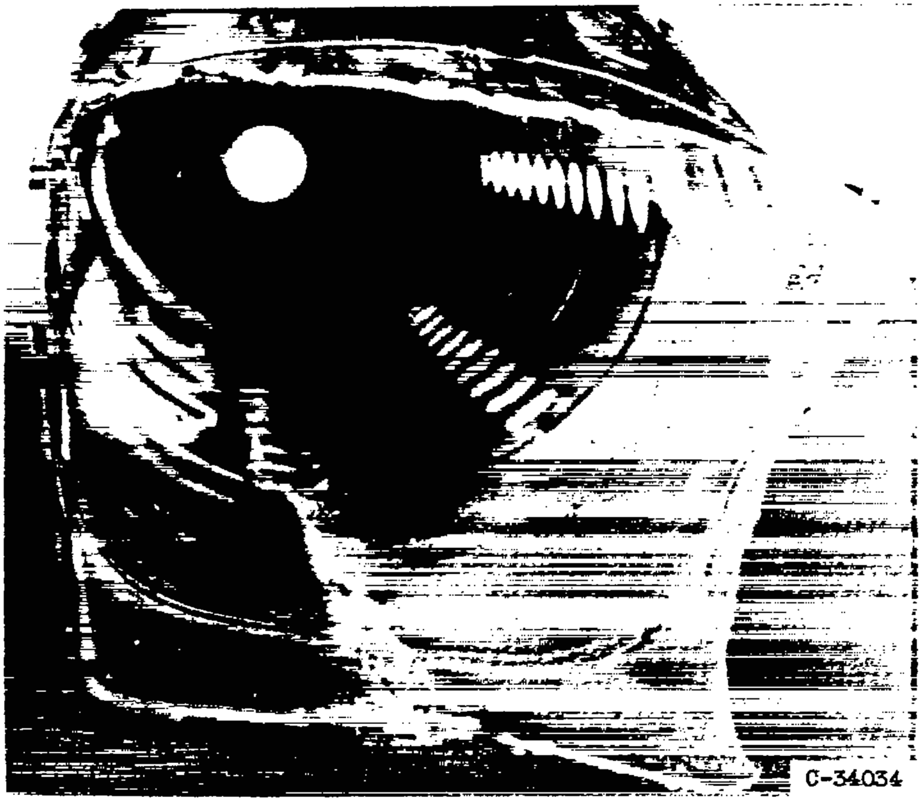


(b) Run 28; model 7 combustor; fuel nozzle II;
test condition C.

Figure 11. - Outlet temperatures. Fuel, 50 percent pentaborane, 50 percent JP-4 blend. (Temperature in °F.)

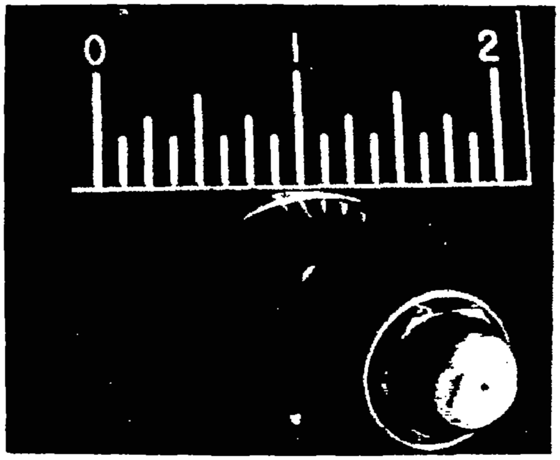


(a) Fuel nozzle.

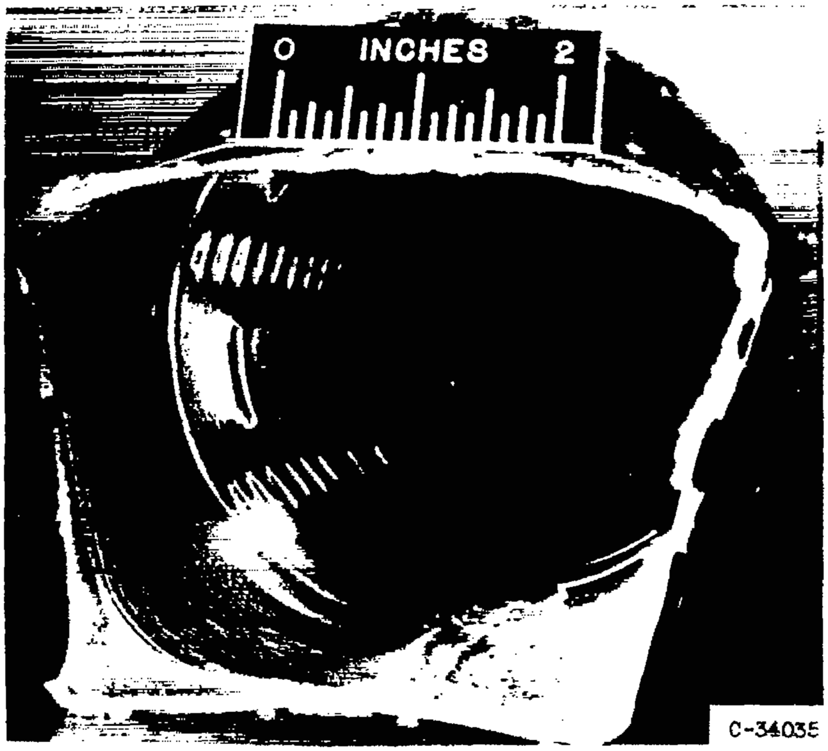


(b) Combustor liner.

Figure 12. - Deposits with model 7 combustor and fuel-injection nozzle II. Fuel, 50 percent pentaborane, 50 percent JP-4 blend; run duration, 6.2 minutes at test condition A.



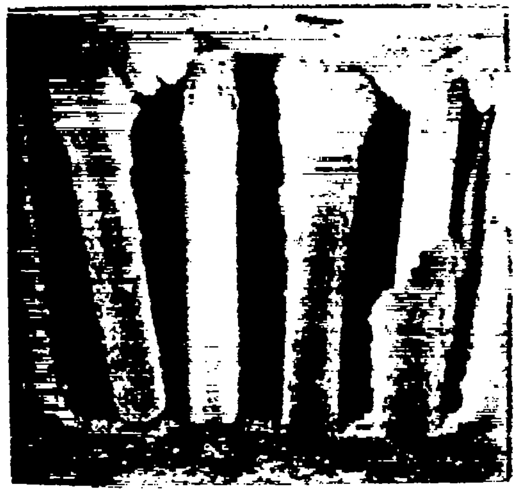
(a) Fuel nozzle.



(b) Combustor liner.

Figure 13. - Deposits with model 7 combustor and fuel-injection nozzle II. Fuel, 50 percent pentaborane, 50 percent JP-4 blend; run duration, 10.6 minutes at test condition C.

(a) Run 25;
model 7 combustor;
fuel nozzle I.



(b) Run 26;
model 6 combustor;
fuel nozzle II.

(c) Run 27;
model 7 combustor;
fuel nozzle II.

Figure 14. - Deposits on special tubes at outlet of combustor at test condition A.

Figure 15. - Deposits on special tubes at outlet of combustor at test condition C.

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